EMPA/BUWAL studies on NO_2 emissions

NO_2 emissions by city buses

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IDRAC 5 October 2004

BUWAL studies on NO_2 (1)

- These studies are not yet published, but released for the use within CARB
- These studies are complete appreciations of the exhaust control technologies
- CRTs show excellent performances in controlling PM mass and number
- But there is a serious concern about NO_2 especially at low load (city driving pattern)

BUWAL studies on NO_2 (2)

- The main purpose of the first study was to check emissions from a Euro 2 engine equipped with a CRT for 7 months (Volvo)
- Reference emissions are those of 1990 (Euro 0) engines recently retrofitted with a CRT (NAW and Mercedes buses)
- Volvo bus was operated with 10 and 50 ppm S, NAW with 50 ppm and Mercedes with 10 ppm

Original report available at EMPA

Report of EMPA on Euro 0 and Euro 2 buses fitted with commercial CRT

Report No. 411289 / 2
Air Pollution / Environmental Technology Laboratory

Contact person at EMPA: Lukas Hemmenegger lukas.hemmenegger@empa.ch

NOx & NO_2 at exhaust of a Mercedes bus fitted with a CRT

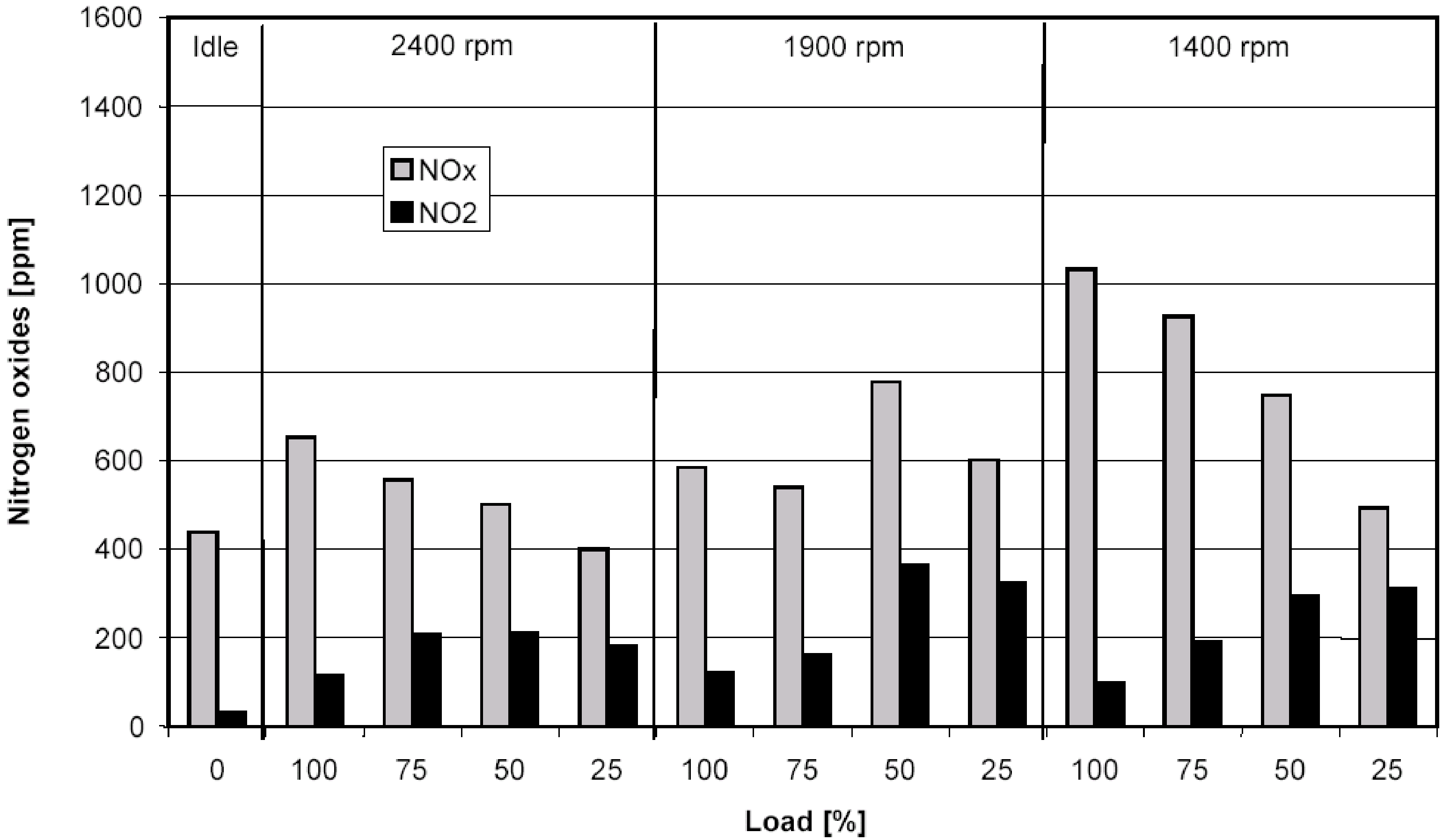

Fig. 1: Nitrogen oxide concentrations from vehicle No.1 (SG 3309, 50 ppm S)

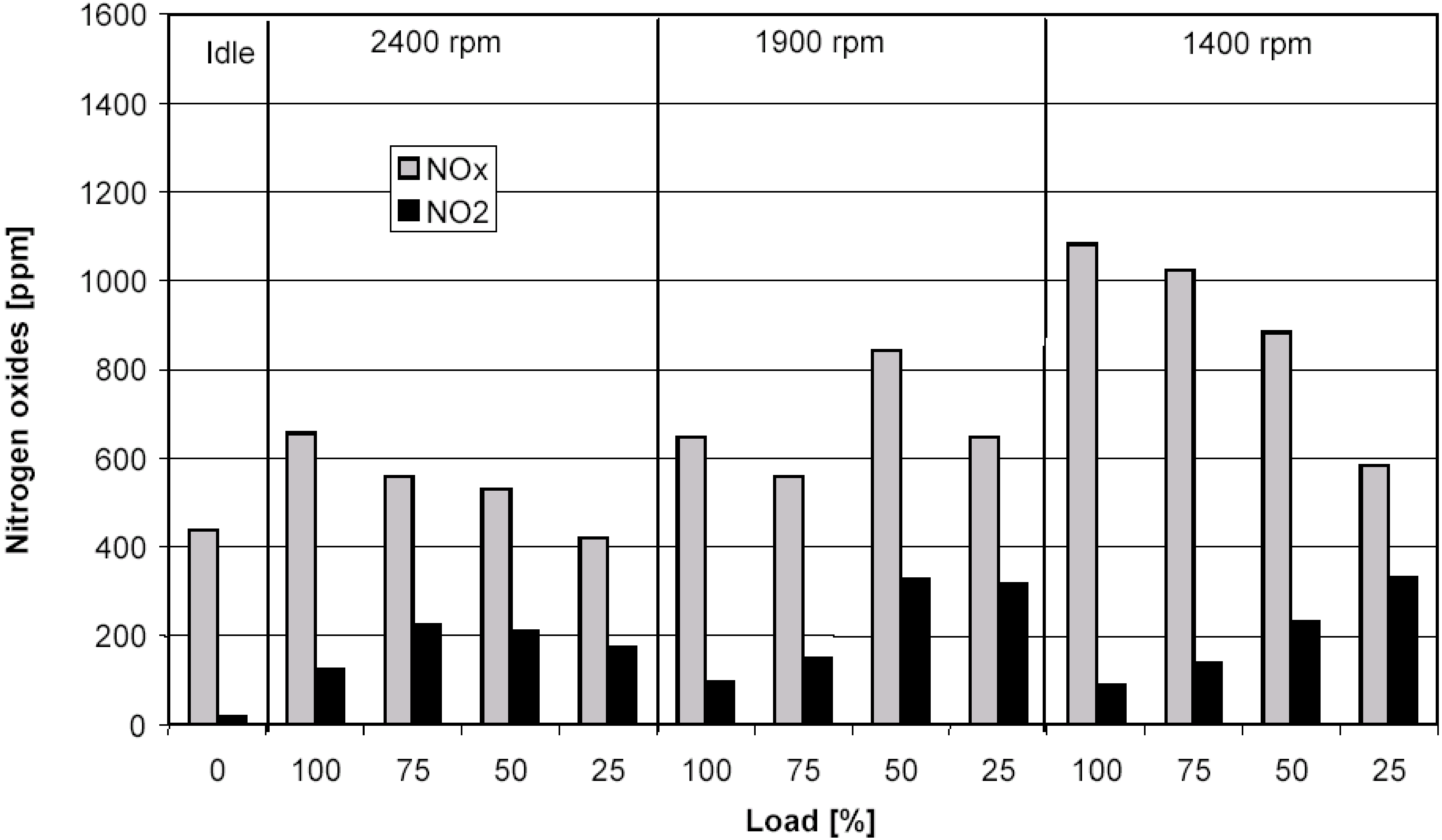

Fig. 2: Nitrogen oxide concentrations from vehicle No. 2 (SG 3309, 10 ppm S)

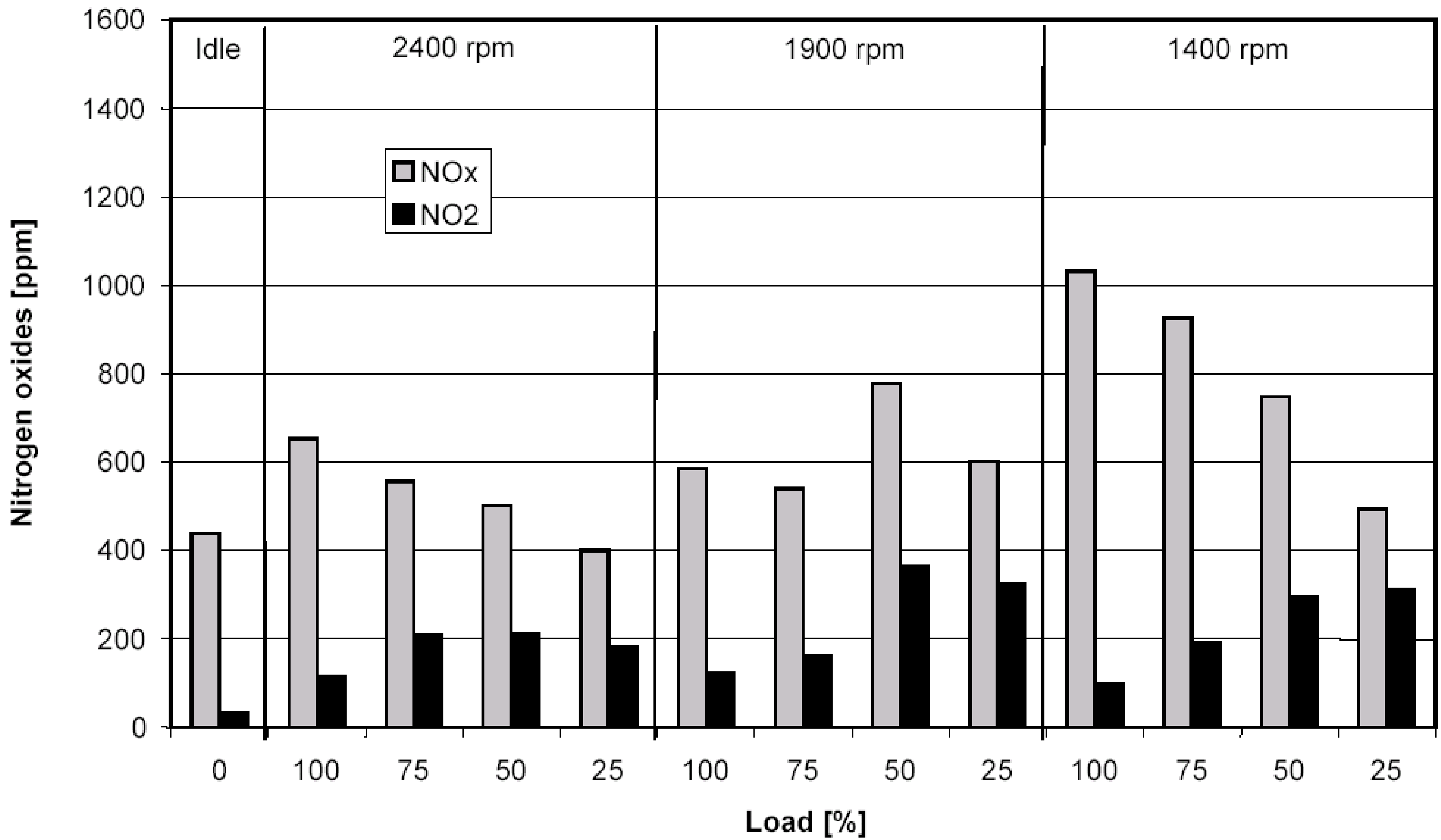

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Fig. 3: Nitrogen oxide concentrations from vehicle No. 3 (ZH 540689)

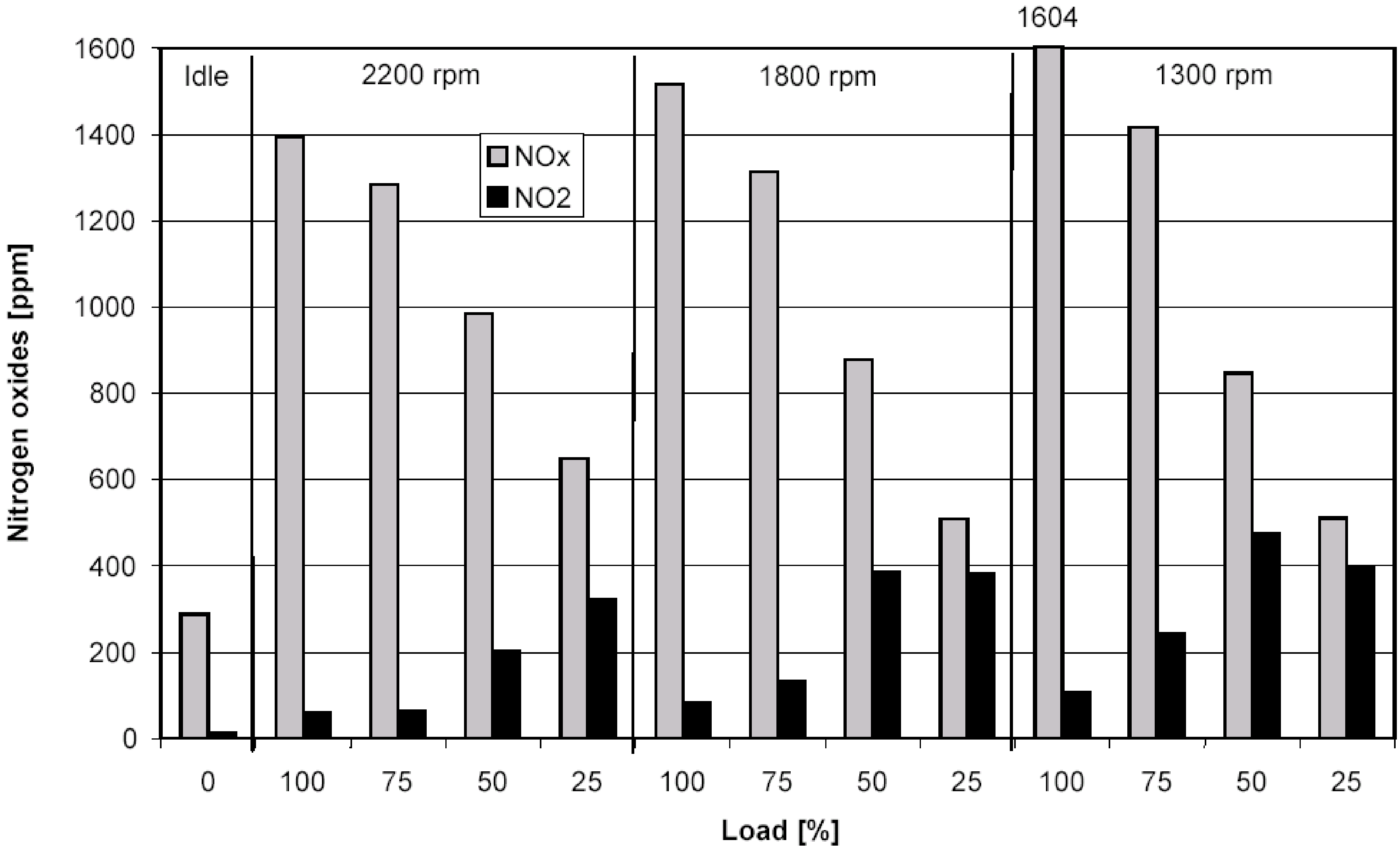


Fig. 4: Nitrogen oxide concentrations from vehicle No. 4 (SG 221820)

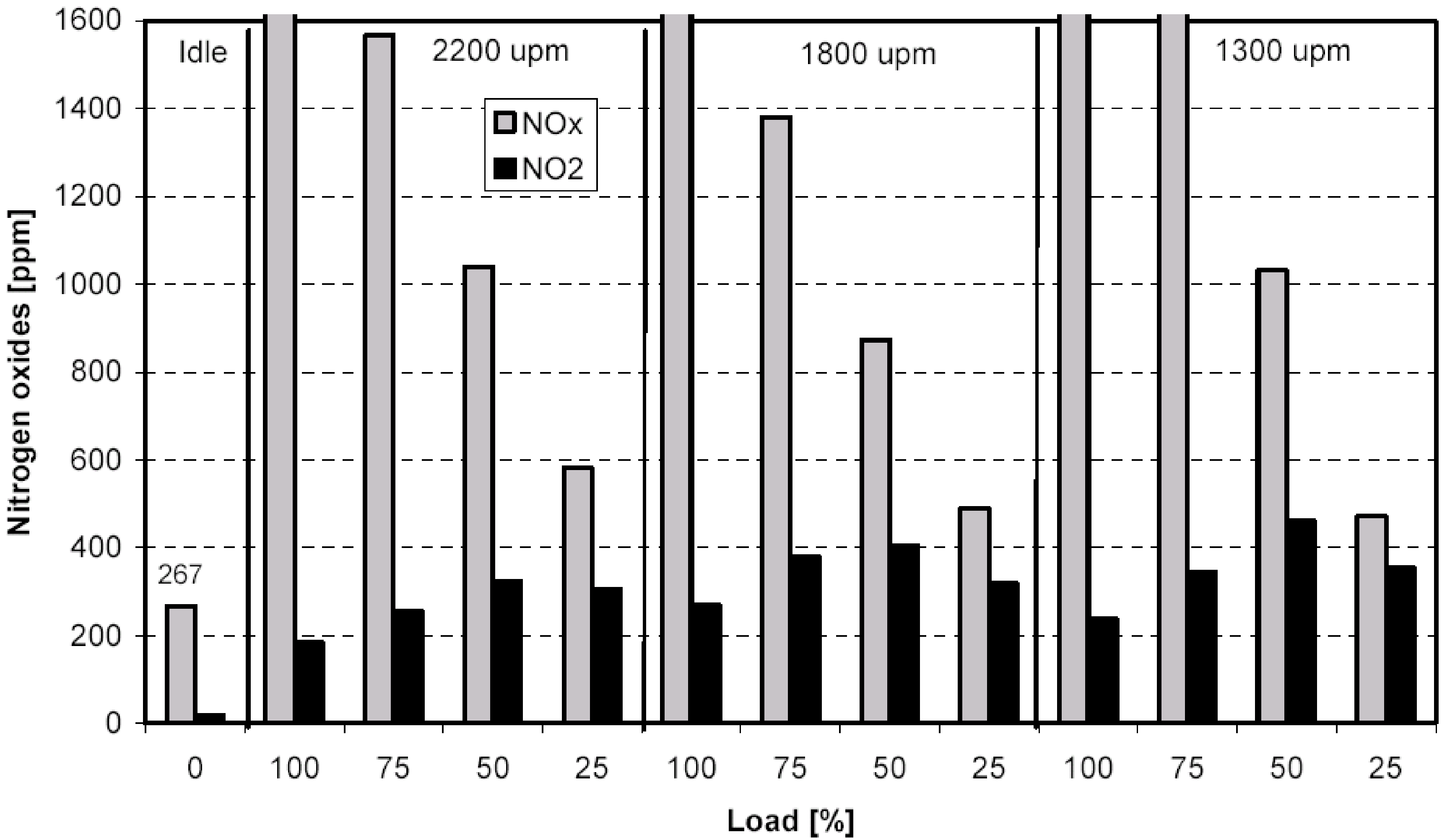


Fig. 5: Nitrogen dioxide fraction vs. load

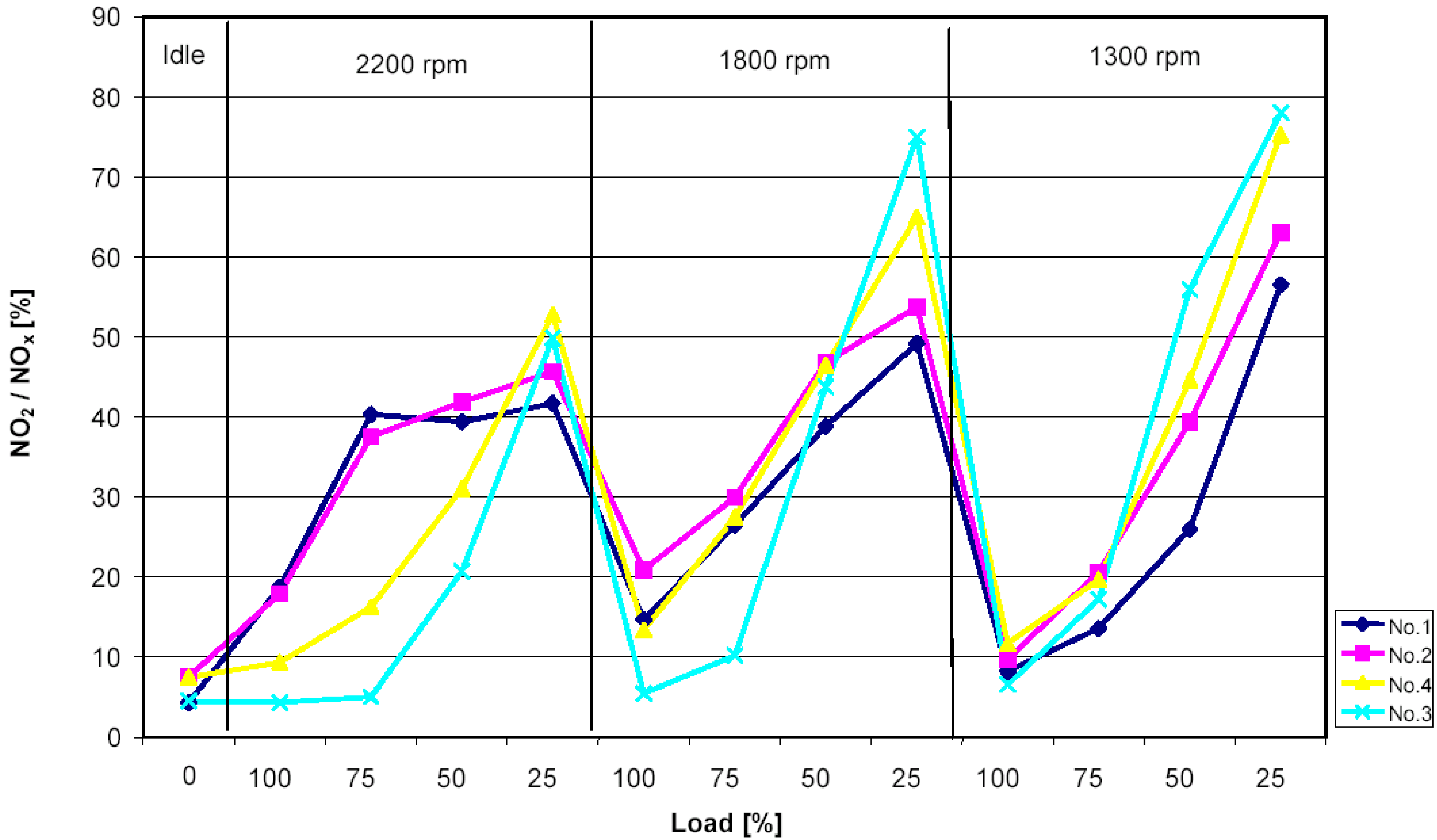


Fig. 6: Nitrogen dioxide concentration vs. load

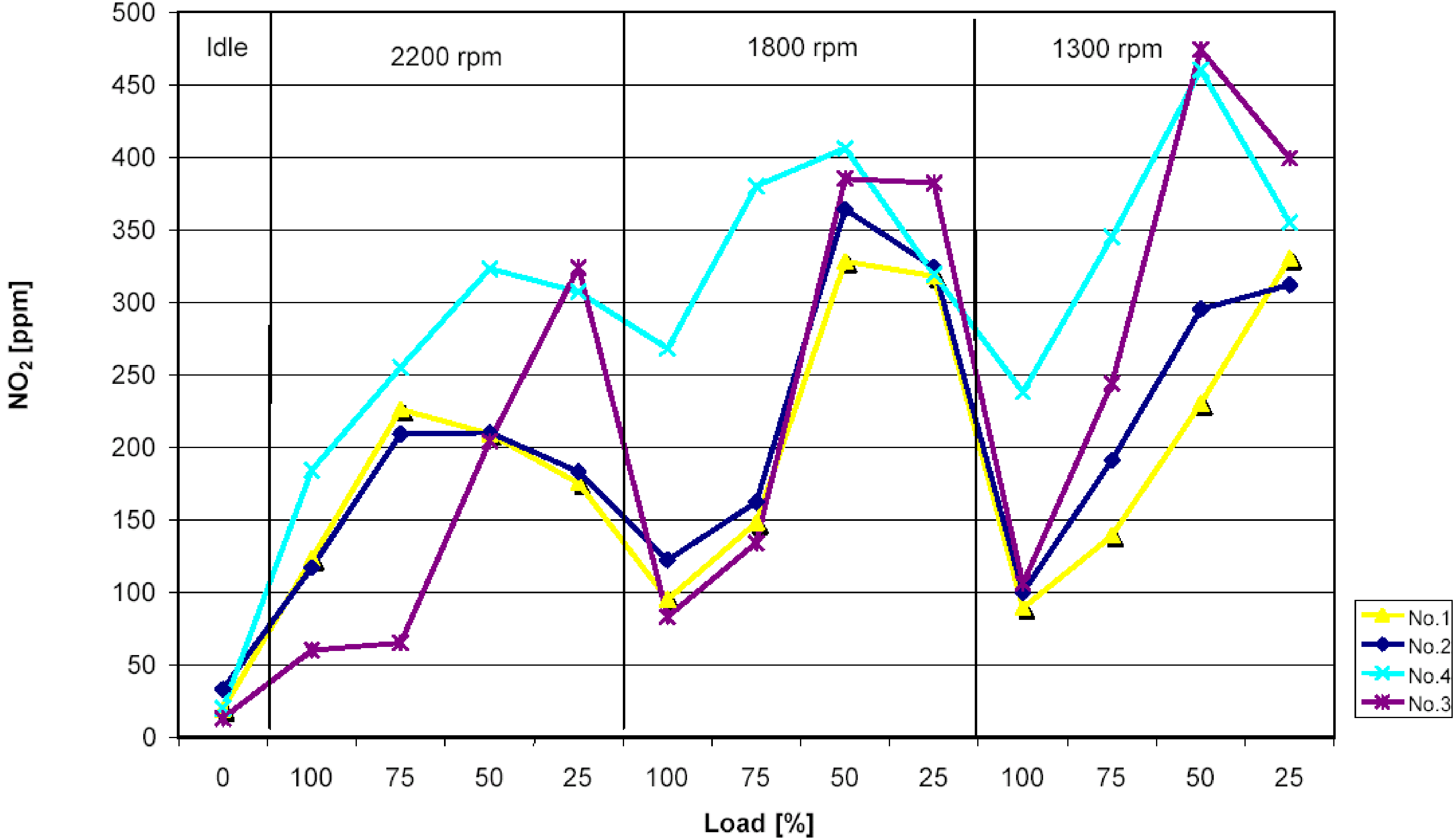


Fig. 7: Nitrogen dioxide fraction upstream and downstream of CRT system

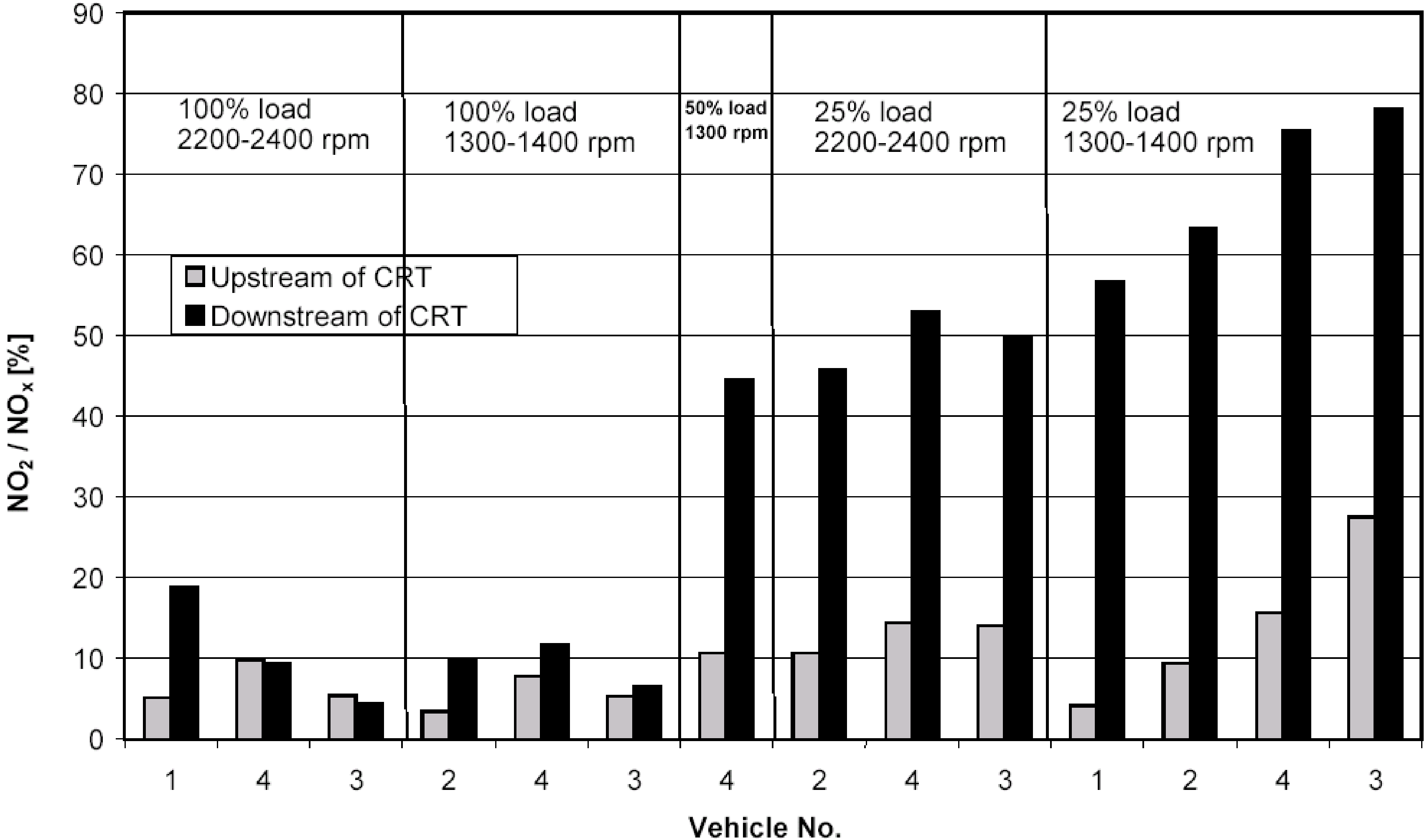


Fig. 8: Nitrogen dioxide concentrations upstream and downstream of CRT system

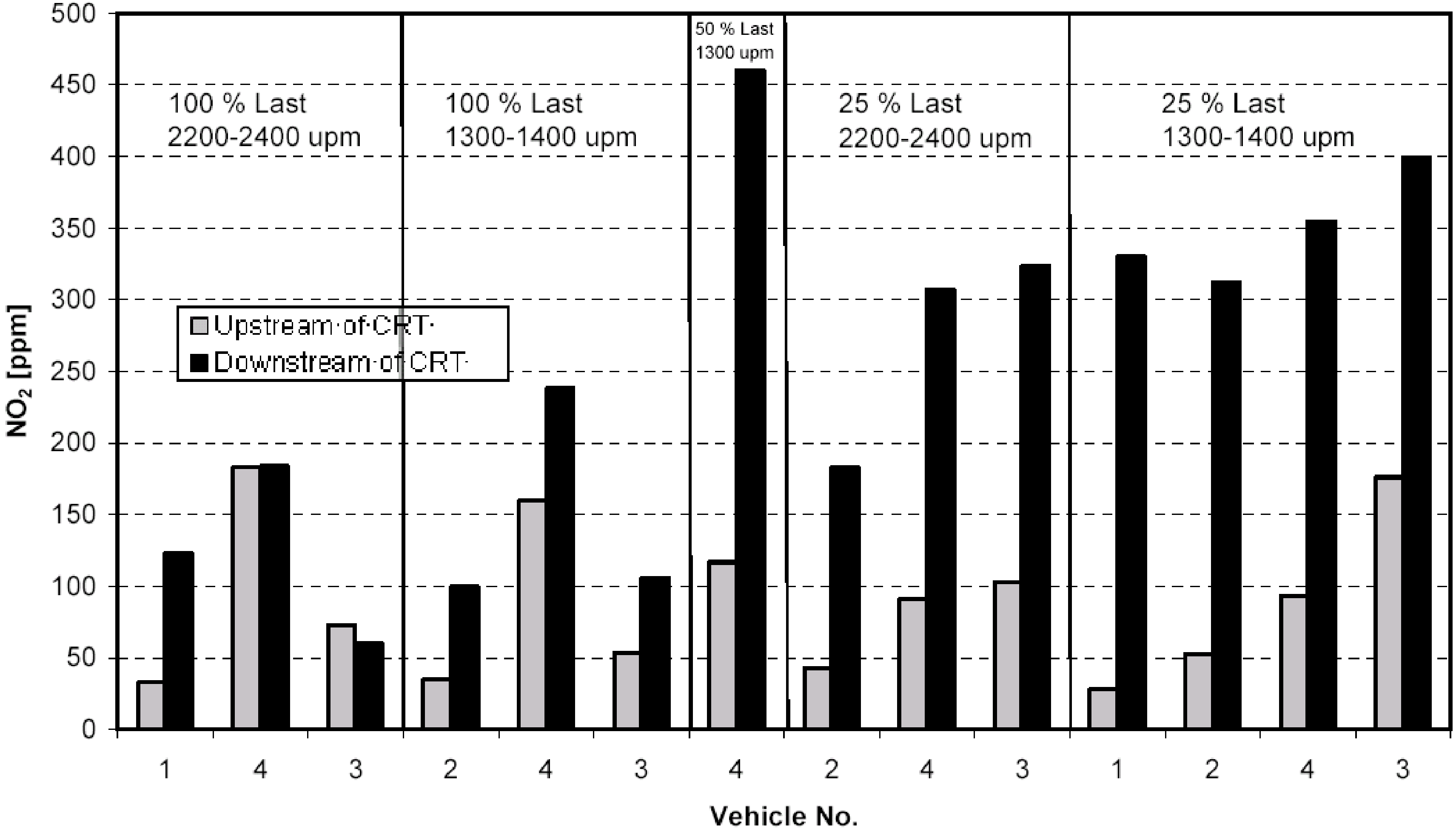
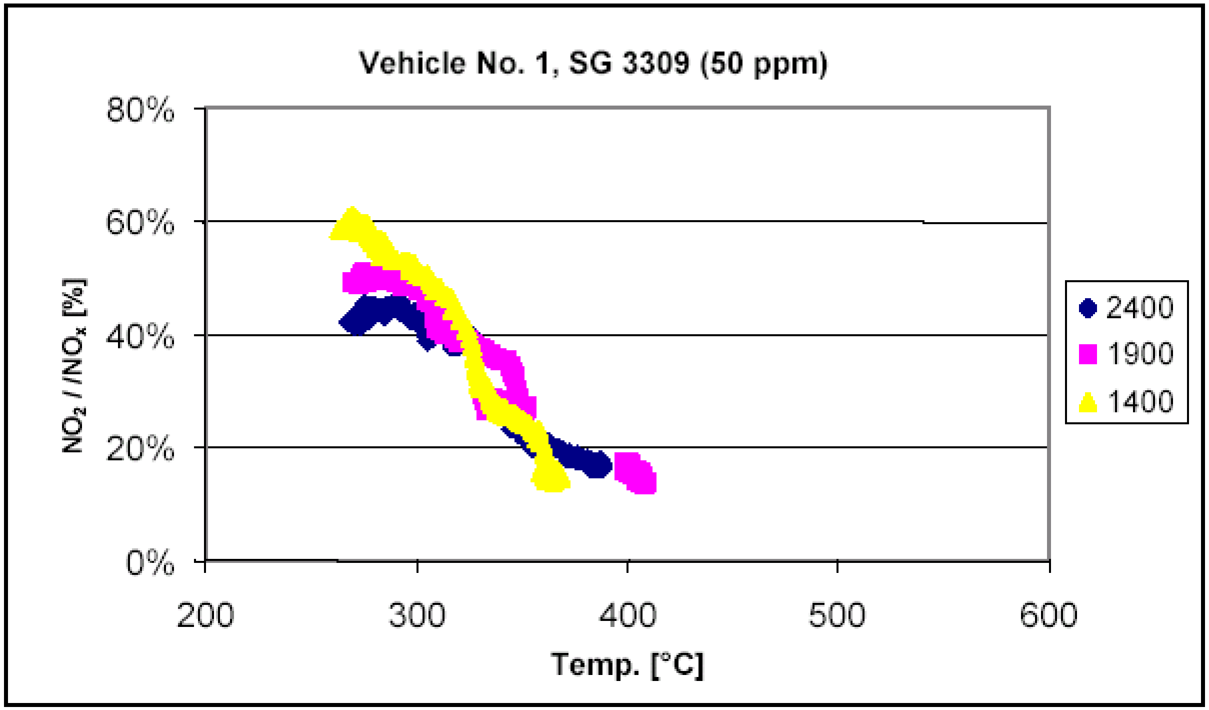
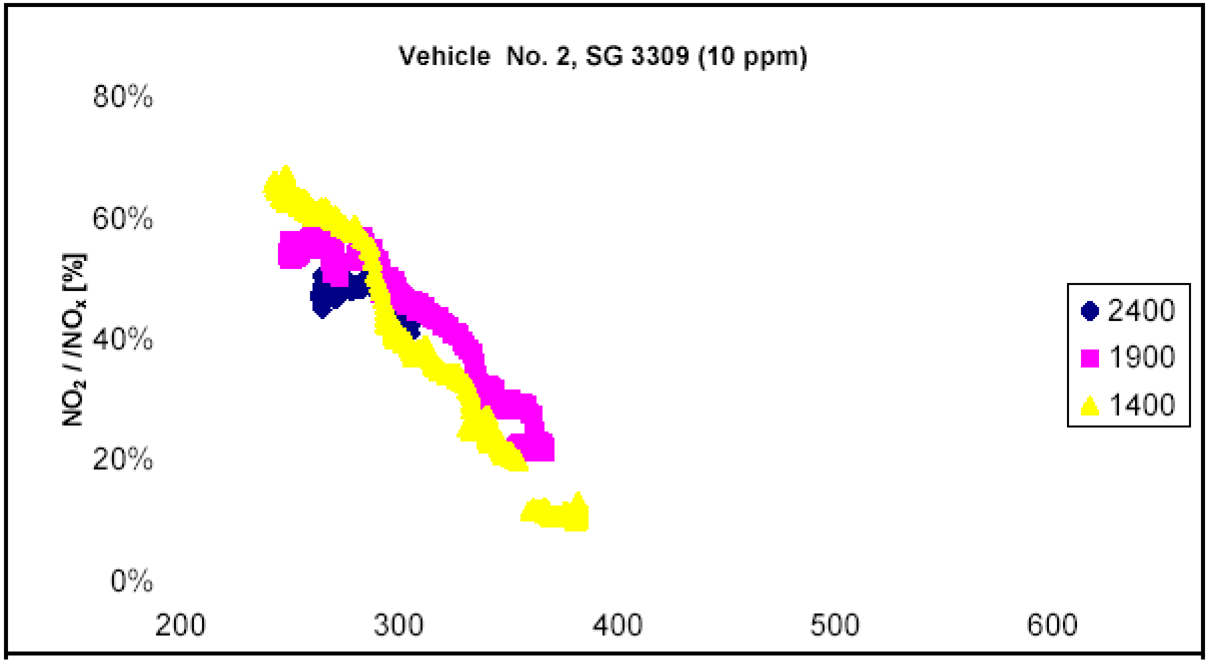
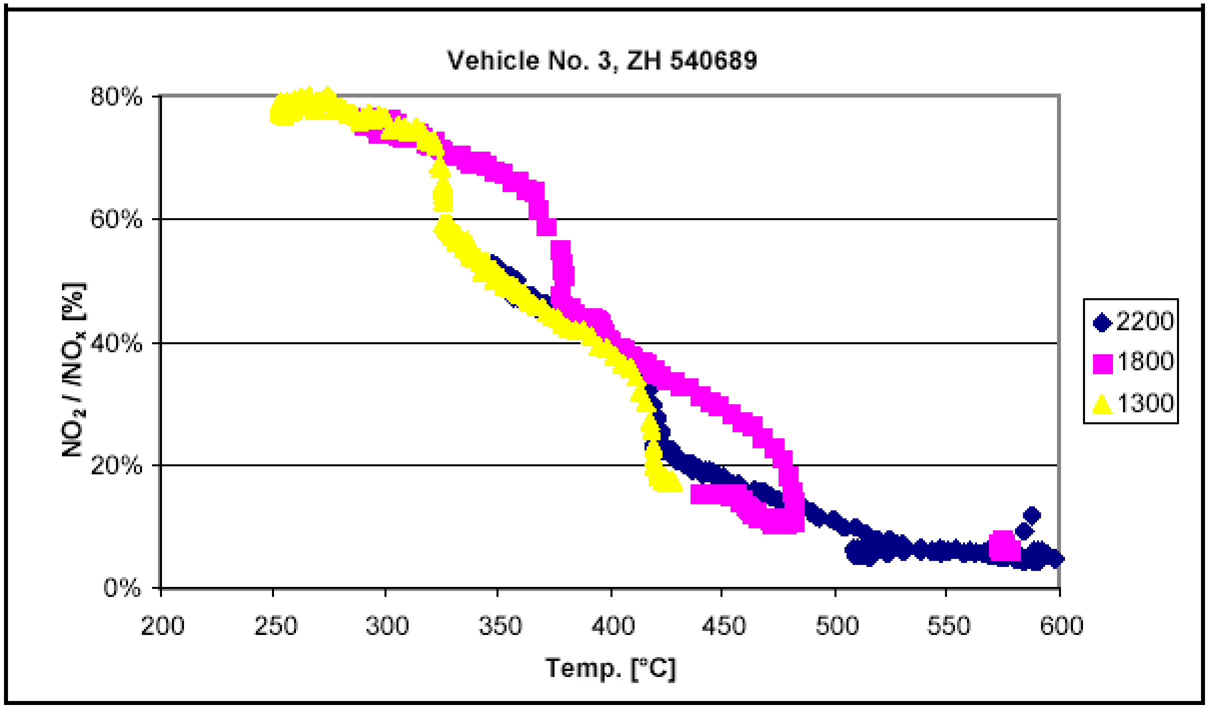


Fig. 9: *Formation of nitrogen dioxide (NO_2/NOx) as a function of exhaust gas temperature and speed*





Vehicle No. 2, SG 3309 (10 ppm)
80%
60%
40%
20%
0%
NO_2 / /NO_x [%]
200
300
400
500
600
2400
1900
1400



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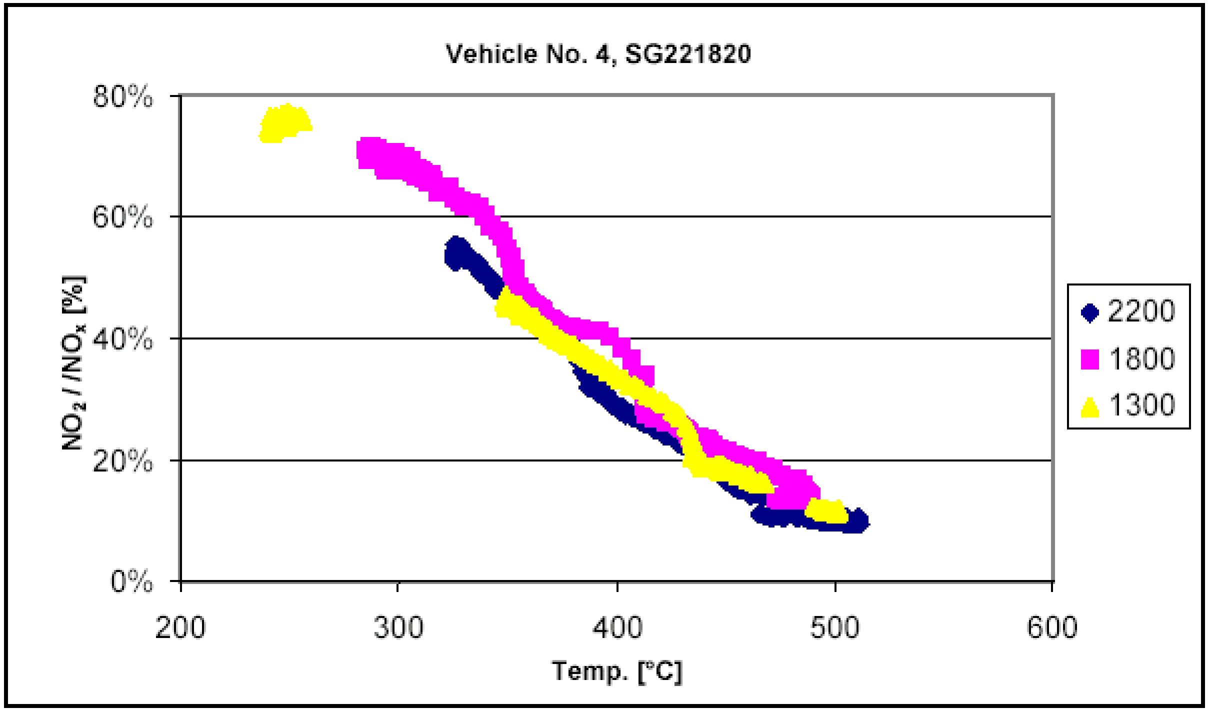


Vehicle No. 4, SG221820
80%
60%
40%
20%
0%
NO_2 / NO_x [%]
200
300
400
500
600
Temp. [°C]
2200
1800
1300

Mains results

- NO_2 /NOx ratio upstream of CRT are highly variable with engine type and operating conditions (5 to 30%)
- Downstream of CRT, at low load & low speed, the ratio can reach 80%, with a lowest at 55%
- Downstream of CRT, at low load & medium speed, the variation from an engine to another one is smaller, ratio are between 45 and 55%
- These areas of engine map are representative of city driving conditions and, in the USA, typical of operating conditions of school buses and urban vehicles.

US perspectives

- No US engines were tested by EMPA, they could behave differently
- Recommendation is to check US engines not on the transient test cycle (mainly representative of highway driving) but on city driving cycles and better on some steady state points which are supposed to induce the highest ratio of NO_2

NO_2 levels are highly dependent of operating conditions

courtesy of VERT

Type of Catalyzed DPF	**CRF #3** mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]	**CRF #4** mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]
2000 rpm / full load	14%	457	153	14%	464	160
2000 rpm / 375 Nm	33%	405	290	30%	406	265
2000 rpm / 250 Nm	57%	332	328	56%	332	300
2000 rpm / 50 Nm	35%	208	68	38%	210	78
1400 rpm / full load	17%	443	330	16%	446	338
1400 rpm / 440 Nm	38%	399	600	28%	397	425
1400 rpm / 292 Nm	64%	317	658	49%	315	440
Idle (790 rpm)	0%	121	0	10%	119	25

Without DPF	mean NO_2/NO_X [%]	mean T5 [°C]	mean NO_2 [ppm]	mean NO_2/NO_X [%]	mean T5 [°C]	mean NO_2 [ppm]
2000 rpm / full load	2%	442	25	6%	447	75
2000 rpm / 375 Nm	2%	392	15	6%	390	58
2000 rpm / 250 Nm	4%	325	23	7%	326	48
2000 rpm / 50 Nm	14%	206	28	19%	207	40
1400 rpm / full load	1%	440	13	5%	442	118
1400 rpm / 440 Nm	0%	396	5	6%	390	103
1400 rpm / 292 Nm	2%	316	25	7%	312	80
Idle (790 rpm)	24%	118	48	25%	116	50

NO_2 emissions with non PGM coated systems

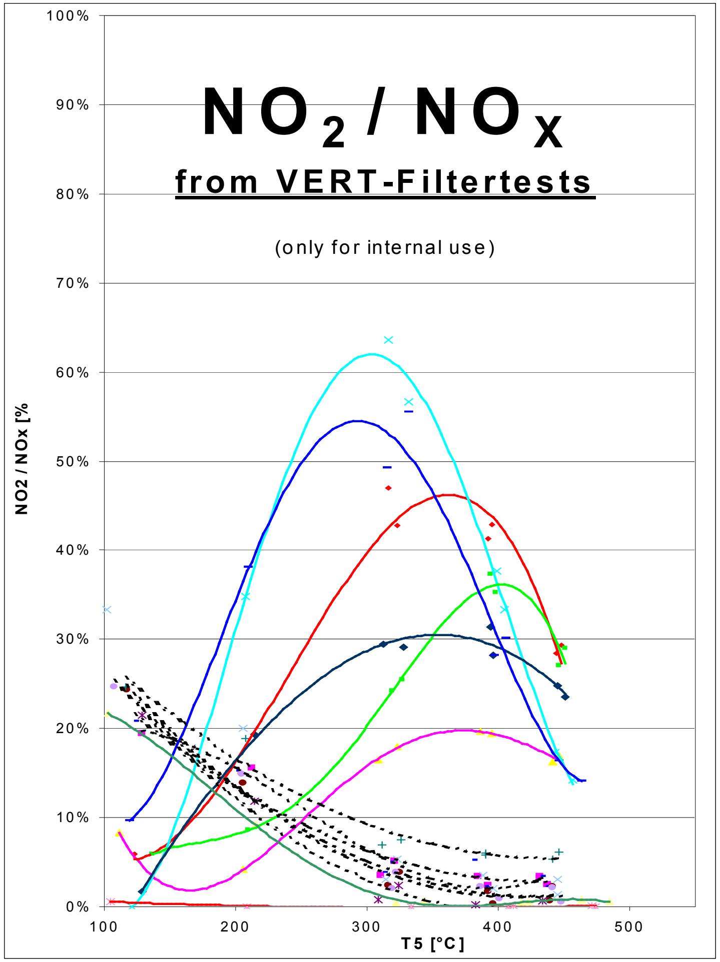
courtesy of VERT

DPF type	Thermal regeneration			Base metal cat DPF + FBC		
	mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]	mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]
2000 rpm / full load	1%	484	8	0%	474	0
2000 rpm / 375 Nm	0%	417	5	0%	408	0
2000 rpm / 250 Nm	1%	343	5	0%	334	0
2000 rpm / 50 Nm	9%	215	23	0%	209	0
1400 rpm / full load	1%	463	18	0%	471	3
1400 rpm / 440 Nm	1%	423	10	0%	411	3
1400 rpm / 292 Nm	0%	323	5	0%	322	-3
Idle (790 rpm)	22%	103	43	1%	105	1

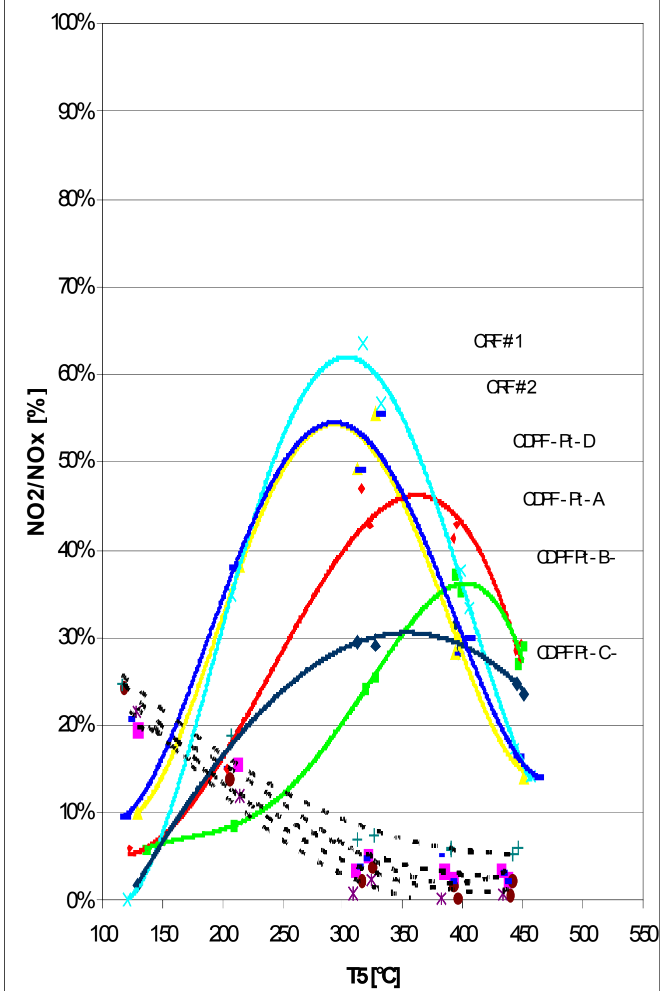
Without DPF	mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]	mean NO_2/NO_X [%]	mean Temp. [°C]	mean NO_2 [ppm]
2000 rpm / full load	3%	445	40	2%	441	30
2000 rpm / 375 Nm	4%	389	35	2%	387	25
2000 rpm / 250 Nm	5%	323	35	4%	322	28
2000 rpm / 50 Nm	20%	206	48	15%	205	35
1400 rpm / full load	1%	445	30	1%	448	13
1400 rpm / 440 Nm	2%	396	38	1%	401	18
1400 rpm / 292 Nm	3%	315	35	2%	320	25
Idle (790 rpm)	33%	102	63	25%	107	50

Overall results on different systems

Recently *courtesy of VERT*



One year ago



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NIOSH report April 1, 2004 on Stillwater mine experiment

<u>During normal mining operations</u>

"Both tests #2 and # 3 were terminated, during the sampling period, due to high concentrations of NO2 detected by the personal multi-gas monitor carried by the operator of the truck #921 *35.* During test #2, while vehicles #92 135 and *#92535* were at the development section, **the monitor showed NO2 concentrations higher than *5* ppm**, the 1973 ACGIH short term exposure level (STEL) for this gas adopted by MSHA (30 CFR *57.5001* 1995). During test #3, when vehicle #92 135 was at the orepass, **the monitor carried by the operator showed concentrations in excess of *5* ppm**. **Elevated NO2 exposures resulted in the removal of personnel from the work area.** Exposures above *5* ppm were not reported during test #4; however, the peak concentrations of NO2 measured at the downstream sampling station (Figure 10) indicate that personal exposures might have been relatively high in this case as well."

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<u>courtesy of NIOSH</u>

NIOSH Stillwater test site

During normal mining operations

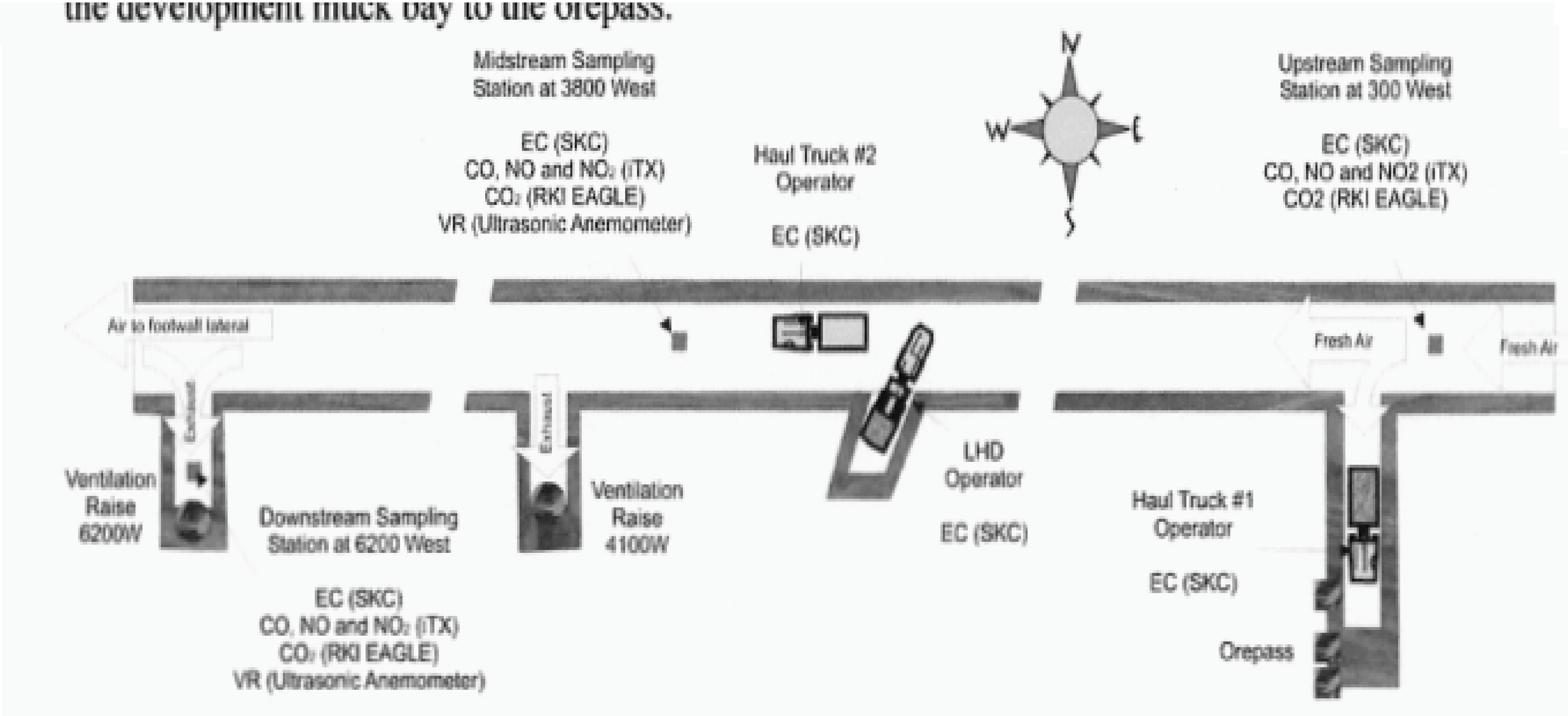


Figure 1. Schematic of the test zone (not to scale)

courtesy of NIOSH

Stillwater in remote gallery

courtesy of NIOSH

<u>Measured in a remote gallery, the tested vehicle being alone</u>

Table 11. Normalized concentrations of carbon monoxide (CO), carbon dioxide (CO2), nitric oxide (NO), and nitrogen dioxide (NO2) at downstream sampling station

Test Type	CO [ppm]		CO_2 [ppm]		NO [ppm]		NO_2 [ppm]	
	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.
#92128 Haul Truck, MSHA vent rate 12000 cfm								
Baseline	11.1	6.7	3834	2924	22.2	16.9	1.1	0.6
Engelhard DPX	0.0	0.0	3793	2718	18.9	12.5	3.2	2.1
#92506 LHD, MSHA vent rate 11500 cfm								
Baseline, D1	18.5	2.3	6268	2104	27.7	5.0	0.9	0.0
Baseline, D2	18.4	2.6	5874	2201	23.0	5.3	0.9	0.0
#92526 LHD, MSHA vent rate 10000 cfm								
Baseline	17.5	6.4	7820	3699	40.8	17.0	2.6	0.9
Baseline / PTX	0.0	0.0	7622	3821	41.3	18.6	2.9	1.0
Biodiesel B20 / PTX	0.0	0.0	7450	3826	40.1	19.3	2.9	1.1
Biodiesel B50 / PTX	0.0	0.0	7622	3855	44.2	21.1	3.5	1.3
#99942 LHD, MSHA vent rate 15000 cfm								
Baseline, D1	24.2	4.5	8740	2849	50.2	13.5	3.1	0.6
Baseline, D2	23.4	4.4	9028	2861	43.3	11.2	2.7	0.5
DCL MineX	0.0	0.0	8656	2713	43.3	11.2	5.7	1.5

Stillwater NO_2 in remote gallery

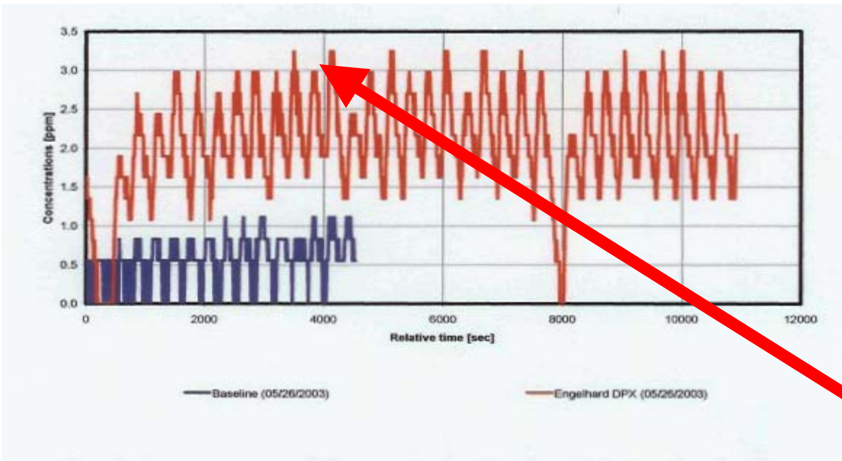


Figure 32. Normalized NO_2 concentrations for the tests with LHD #92128

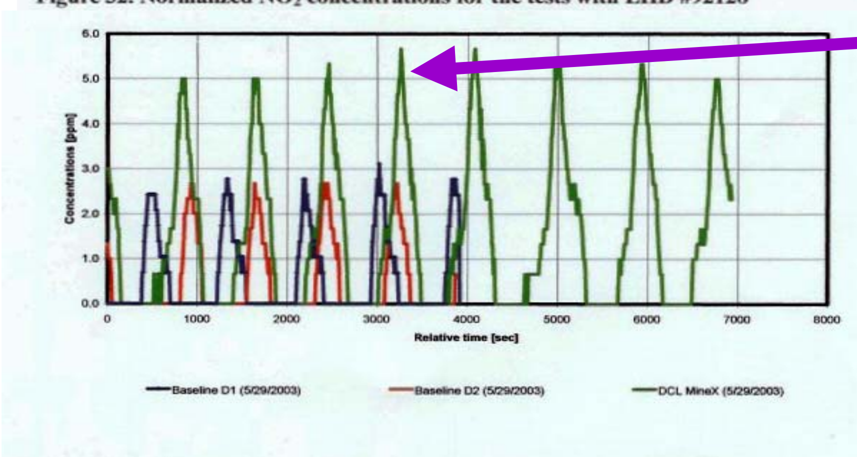


Figure 33. Normalized NO_2 concentrations for the tests with LHD #99942

- With only one vehicle equiped with commercial CDPF in a remote gallery, the limit of 3 ppm, which is the legal exposure during 15 mn, is regularly met or even exceeded
- Engine base lines varie but for the people exposed to the emission the only valid limit is the threshold of exposure

courtesy of NIOSH

Original report available at EMPA

Report on FBC (Octel) + base metal catalyzed SiC filter (Haldor Topsoe)

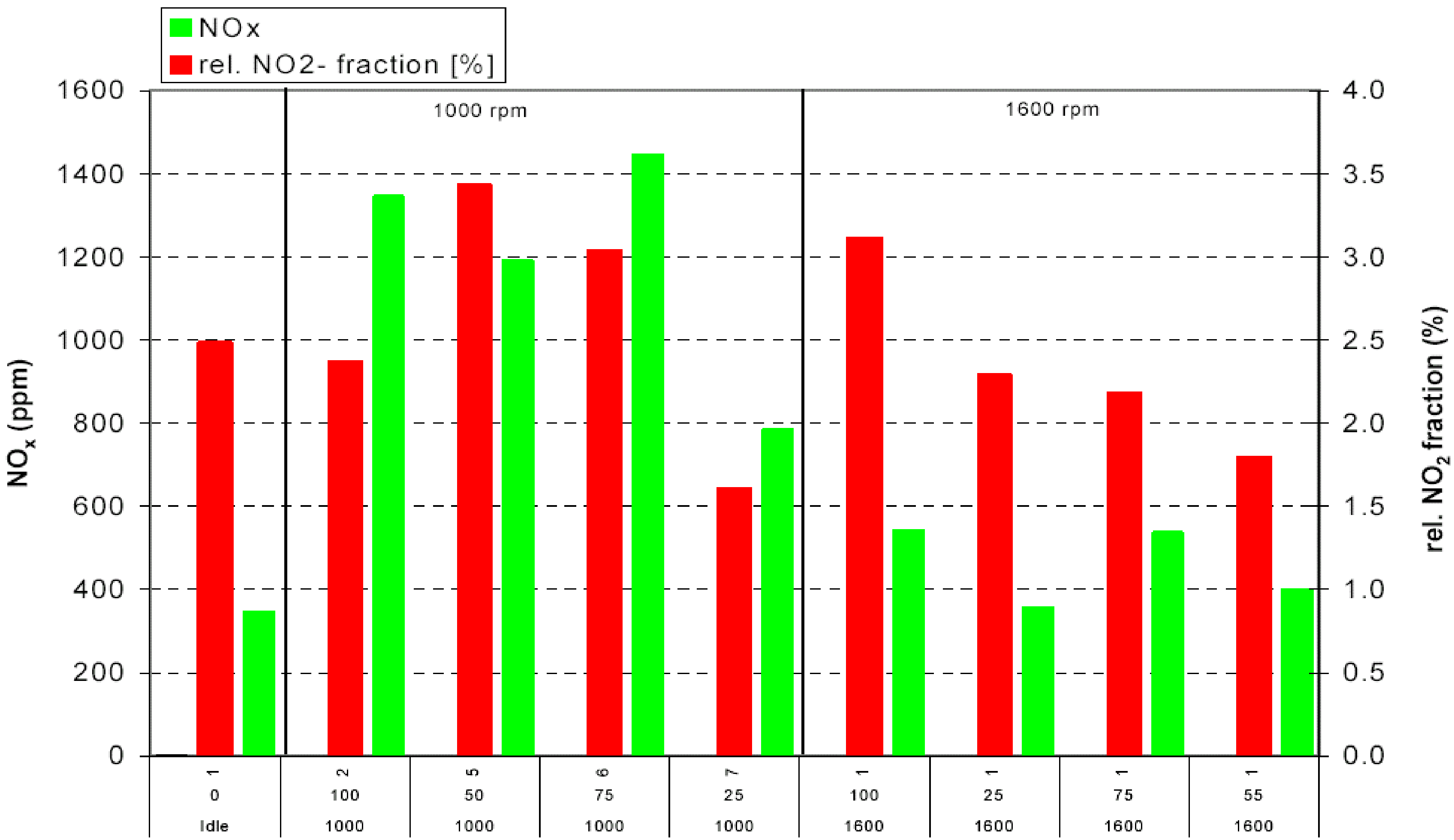
Report No. 433'356
Air Pollution / Environmental Technology Laboratory

EMPA

Contact at EMPA: Lukas Emmenegger lukas.emmenegger@empa.ch

Alternative system with FBC

Figure 1: Ratio of nitrogen oxide concentrations downstream of filter



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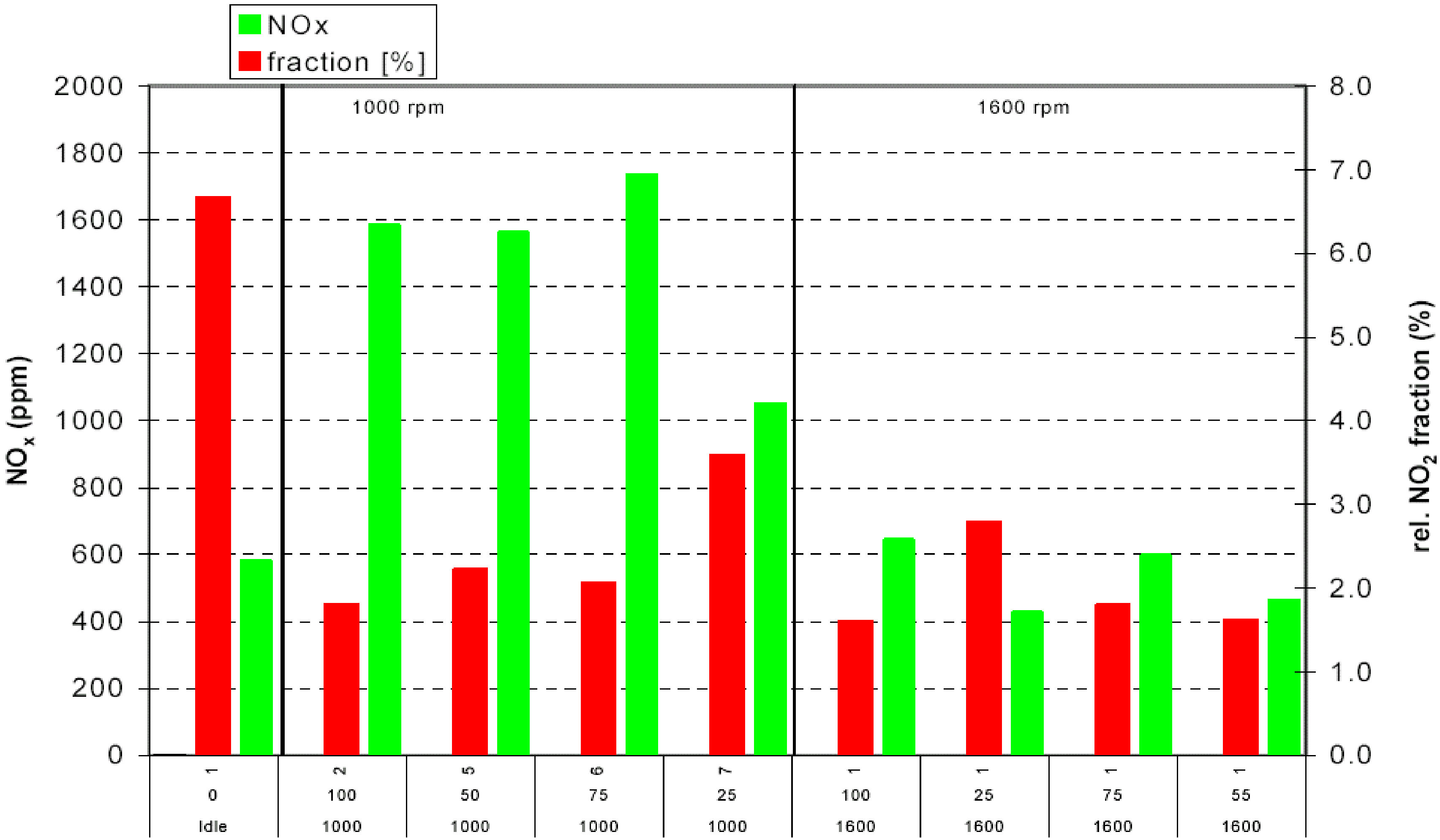
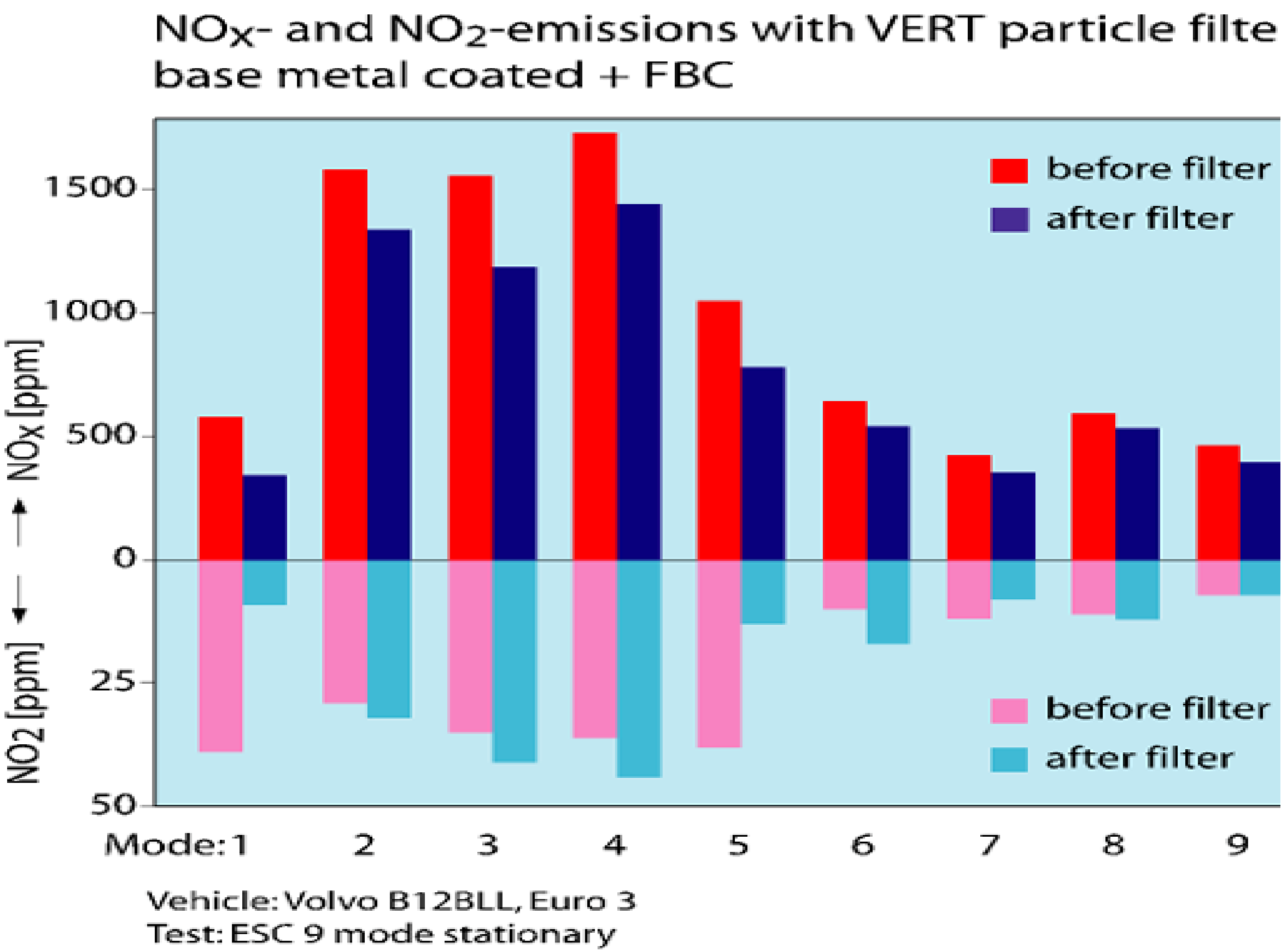
Alternative system with FBC

Figure 2: Ratio of nitrogen oxide concentrations upstream of filter



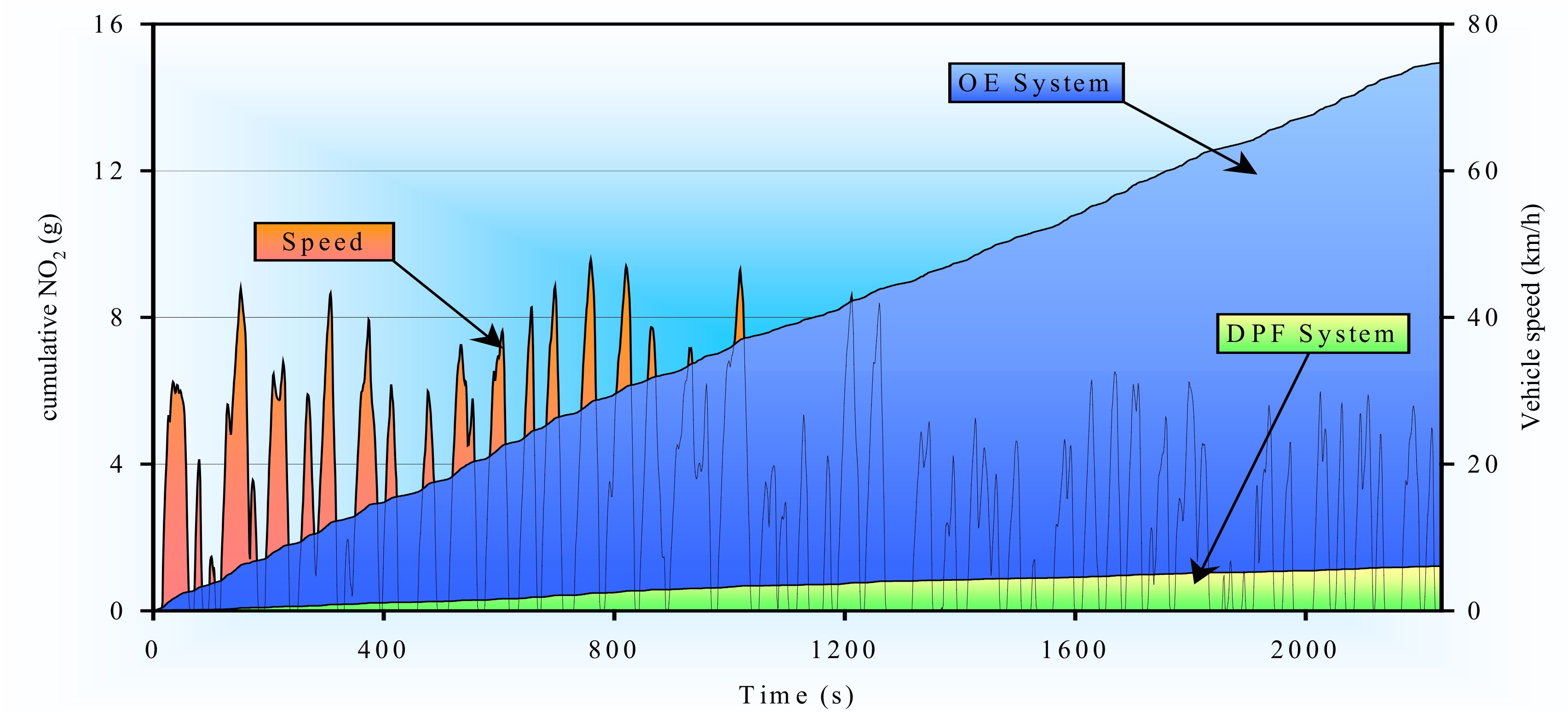
Alternative system with FBC on a Euro 3 bus



Further field application of DPF + FBC

Cumulative NO_2 emissions

courtesy of ADASRA-OCTEL



Hot or cold measurements of NOx and NO_2

- Temperature of gases is a key factor of accuracy when measuring NOx and NO_2
- NO_2 value is in fact NOx – NO
- Following graphs are extracted from a Swiss study (Biel University) and show the huge influence of temperatures
- Another conclusion is that FBC does not produce NO_2, while CRT produces a lot especially detectable in hot gas flow

Hot and cold measurements Discussion

- It is hardly believable that only a change of temperature can justify this difference in NO_2 levels: we believe that explanation is more likely in the fast reactivity of NO_2 with water to give HNO_3 which is no more measured as NOx
- If there is some condensed water in cold measurement circuit, the level of NOx which is measured is reduced and therefore the level of NO_2

NOx & NO_2 with CRT

courtesy of Biel University

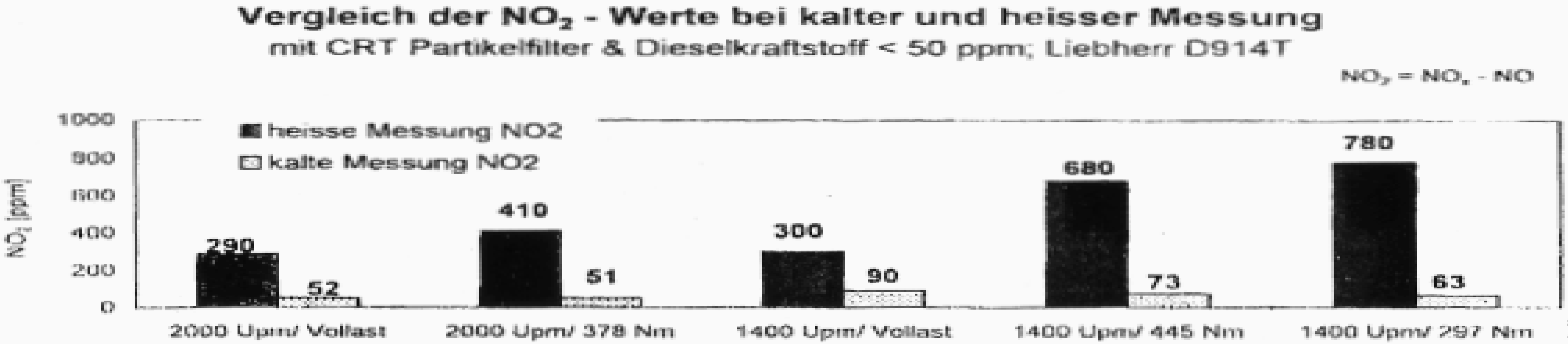


Figure 3

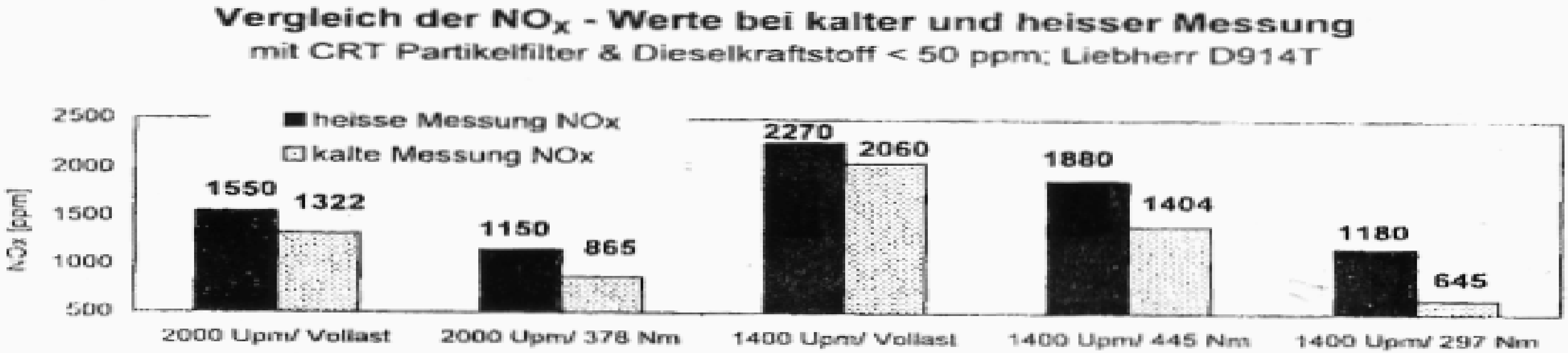
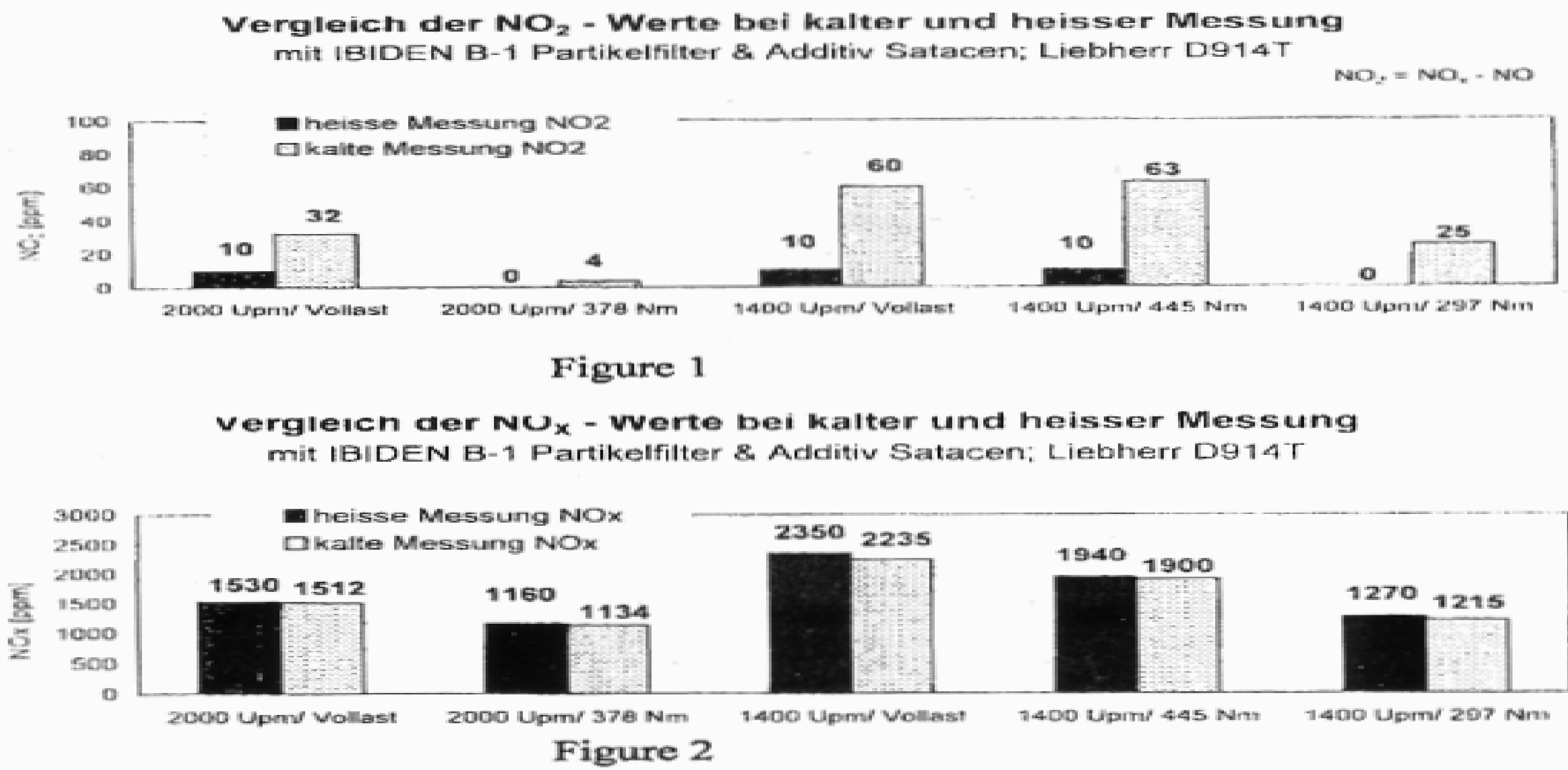


Figure 4

NOx & NO_2 produced by FBC

courtesy of Biel University



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Discussion (1)

- No discussion about the necessity to eliminate the PM by using appropriate filters
- The discussion about counting or not the liquid droplets represent a risk to delay any decision while most of the specialists in health effects admit today that the droplets have a risk factor which must be related with their mass, while solid soot risk must be related with size and number

Discussion (2)

For BUWAL appropriate means:

- filters efficiencies must be also measured by number in order to eliminate problems linked with mass measurements (but mass measurement must be kept for reference)
- ability to avoid formation of NO_2 in all operating conditions must be a bonus in the process of verification of exhaust controls
- not to exceed limits have to be defined on city driving cycles or on steady state tests

Conclusions (1)

- Filter efficiency must be qualified by ability to remove all categories of soot particles from the exhaust stream (only number give an accurate rating)
- Exposure risks due to high levels of NO_2 emissions downstream of DOCs and filter systems containing Platinum must be taken in account in any verification procedure

Conclusion (2)

- Measuring NO_2 on transient cycles does not reflect the risk of exposure in micro-environnements (cabin of vehicles or buses, spot places where school buses or urban vehicles agglomerate, road tunnels)
- Only measurements on selected steady states (for the same reason EST was introduced in certification (NOx) of HD engines) together with NTE limits will give an accurate evaluation of risks

Discussion (3)

- Another approach could be to measure NO_2 on city driving cycles, as developed in certain cities. These cycles include a majority of low speed / low load engine operating conditions where the formation of NO_2 is maximum
- It could be premature to define any type of regulation before achieving individual exposure risk evaluation in field conditions

Acknowledgements

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